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Late Pliocene-Pleistocene environments and glacial history of the northern North Sea

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ABSTRACT

Based on new geochronological (amino acids and Sr-isotopes) and lithological data combined with analyses of 3D seismic data, the Pliocene-Pleistocene development of the central northern North Sea has been investigated. At the start of the Plio-Pleistocene Transition the study area was dominated by a deltaic, shallow marine or tidal depositional environment with sediments mainly sourced from the west. These sand-rich sediments include green glauconitic grains that belong to the Utsira Sand with a local provenance. Directly above the base Quaternary (R2) a 60 m thick layer of mud-rich sediments of glacimarine origin were deposited at a rate of ~12 cm/ka between ~2–1.5 Ma and up to 80 cm/ka between 1.5 and 1.2 Ma possibly reflecting glacial ice advancing to the Norwegian coastline. The high rate of deposition in the Early Pleistocene occurred immediately before the initiation of the Norwegian Channel Ice Stream at ~1.1 Ma. Following this, a large part of the sediment input from Fennoscandia seems to have been directed away from the study area to the shelf break. At the start of the Mid Pleistocene Transition (MPT), subaerial conditions allowed the formation of a >50 km long fluvial channel across the study area draining water from the east to the south west. The earliest evidence of grounded ice in the investigated area comes from mega scale glacial lineations formed during the MPT, at or just after ~1.2 Ma. Following this, a regional unconformity (R4) was formed by one or more grounded ice advances across the study area possibly during or directly after the MPT and likely marks the boundary between the Early and Mid Pleistocene glacimarine sediments. The Mid to Late Pleistocene stratigraphy is dominated by glacimarine sediments and tills and is associated with multiple generations of tunnel valleys observed within the seismic data. A high shear strength till containing chalk clasts transported from the west and/or south of the study area was likely deposited during MIS6 and may have been more conducive to tunnel valley formation in comparison to lower shear strength tills deposited by later ice advances. A thick till unit overlain by a sand layer in the study area was deposited by grounded ice during the Last Glacial Maximum and subsequent drainage of an ice dammed lake in the southern North Sea during the last deglaciation (MIS2) of the study area. This study shows that much of the Quaternary age sediments within the northern North Sea were deposited relatively rapidly during short periods of time probably leaving significant hiatuses within the stratigraphic record. This finding has implications for previous studies that use a chronological framework assuming a relatively continuous sedimentation rate and record for the Early Pleistocene within the North Sea.

1. Introduction

Recently there has been renewed interest, both from academia and industry, in the Quaternary depositional history of the North Sea. Up to 1 km of Quaternary age sediments reflects the subsidence of the North Sea Basin (NSB), the uplift and erosion of the Fennoscandian Shield, and the timing and magnitude of ice sheet build-up and decay over the UK, Scandinavia and NW Europe (Huuse, 2002a,b; Anell et al., 2010, 2012; Graham et al., 2011; Westaway, 2016). A good understanding of the Quaternary

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history of the North Sea is also important because of its implications for petroleum exploration and CO_2-storage (Chadwick et al., 2004). Significant improvements in seismic acquisition and processing, particularly in relation to 3D seismic surveys, has now enabled far greater resolution of the upper sedimentary layers (<1 km) (e.g. Sirgue et al., 2010; Morgan et al., 2013; Lu et al., 2015). Despite this, lithological and chronological controls on the NSB Quaternary succession are limited as most industry wells commonly are not sampled or logged through the upper ~1 km although some information exist for the upper 200 m from shallow boreholes that span the last ~1 Ma. Thus, the interpretations of depositional environments for most of the Early to Mid Pleistocene mainly rely on interpretation of seismic data (e.g. Ottesen et al., 2014).

The aim of this paper is to use seismic data and sediment samples to contribute to our understanding of the Late Pliocene - Quaternary (3.6–0 Ma) depositional setting of the central northern North Sea including key global climatic transitions at the Plio-Pleistocene and Mid Pleistocene (Fig. 1A). To achieve this, an exploration well and a neighbouring shallow borehole have been sampled for dating and lithological analyses. This allows chronological tie points to be identified for the seismic stratigraphy which can be extended across a wider area of the NSB and which also enable interpretation of the changing sedimentary input and depositional environment through time.

2. Regional setting

The northern North Sea (Fig. 1A) represents a rift basin, formed during major tectonic periods in the Permian - earliest Triassic and during the late Mid Jurassic-earliest Cretaceous (Faleide et al., 2002). By the end of the Cretaceous, post-rift tectonic subsidence had ceased, forming a wide, sagged basin where up to 2500 m of Cenozoic sediments have been deposited (Faleide et al., 2002).

The Cenozoic sediments within the northern NSB have previously been divided into ten seismic units, CSS-1 to CSS-10, by Jordt et al. (1995) with CSS-8, CSS-9 and CSS-10 consisting of Pliocene-Pleistocene sediments that approximately equate to seismic units MU6, MU7 and MU8 of Rundberg and Smalley (1989), SU3, SU4 and SU5 of Jackson and Stoddart (2005) and NEO3 and NEO4 of Anell et al. (2010, 2012). The Cenozoic sediment package has been sourced from the emergent East Shetland Platform (ESP) (Fig. 1B) and the Scottish Highlands in the west, the Norwegian mainland in the east and from large river systems in the south (Gabrielsen et al., 2010). Subsidence rates of around 0.6–0.9 m/ka have been estimated for the Late Cenozoic (Clark, 1973; Sejrup et al., 1987) providing accommodation space for a 200–1000 m thick unit of Quaternary age sediments to be deposited (Gabrielsen et al., 2001; Anell et al., 2010, 2012; Eidvin et al., 2013; Ottesen et al., 2014). Shifts in depocentre locations, outbuilding directions and sediment composition within the NSB through Cenozoic times have been related to differential vertical movements of the ESP and the Norwegian mainland and variation of clastic sources within these areas (Jordt et al., 2000; Faleide et al., 2002). However, it is debated to what extent the uplift is purely a result of long term glacial erosion and rebound, or if there is also a tectonic component (e.g. Lidmar-Bergström and Bonow, 2009; Nielsen et al., 2009).

The Plio-Pleistocene Transition (PPT) marks the start of intensification of Northern Hemisphere glaciation (Lisiecki and Raymo, 2005) that further increased with the transition from 41 ka to 100 ka glacial interglacial cycles at the Middle Pleistocene Transition (MPT, 1.2–0.75 Ma) (Clark et al., 2006; McClymont et al., 2013; Gulick et al., 2015). During the PPT and Early Pleistocene, ice sheets built up over both the British Isles and Scandinavia with glacimarine conditions within the NSB (Sejrup et al., 2005; Ehlers and Gibbard, 2008). In the Early Pleistocene there is also evidence of cooling in the deep North Atlantic (Sosdian and Rosenthal, 2009). The first direct evidence of grounded ice in the North Sea occurs during the MPT from investigation of a well-dated shallow borehole penetrating till units within the Norwegian Channel, the oldest of which is ~1.1 Ma in borehole 8903 (Fig. 1A) (Sejrup et al., 1989, 1995). The MPT is a period of intense global cooling during both glacial and interglacial cycles (McClaymont et al., 2013). During the MPT grounded ice may have advanced into the NSB but was possibly relatively constricted in comparison to Middle to Late Pleistocene times when the most conspicuous evidence of large scale basin-wide glaciation is found, with numerous generations of buried channels that have been interpreted as ice marginal tunnel valley features (Praeg, 2003 and references there in). The interpretation of basin-wide glaciation also corresponds with the $\delta^{18}O$ record from the North Atlantic which indicates a gradual increase in ice volume during glacial cycles from 0.9 to 0.6 Ma (Sosdian and

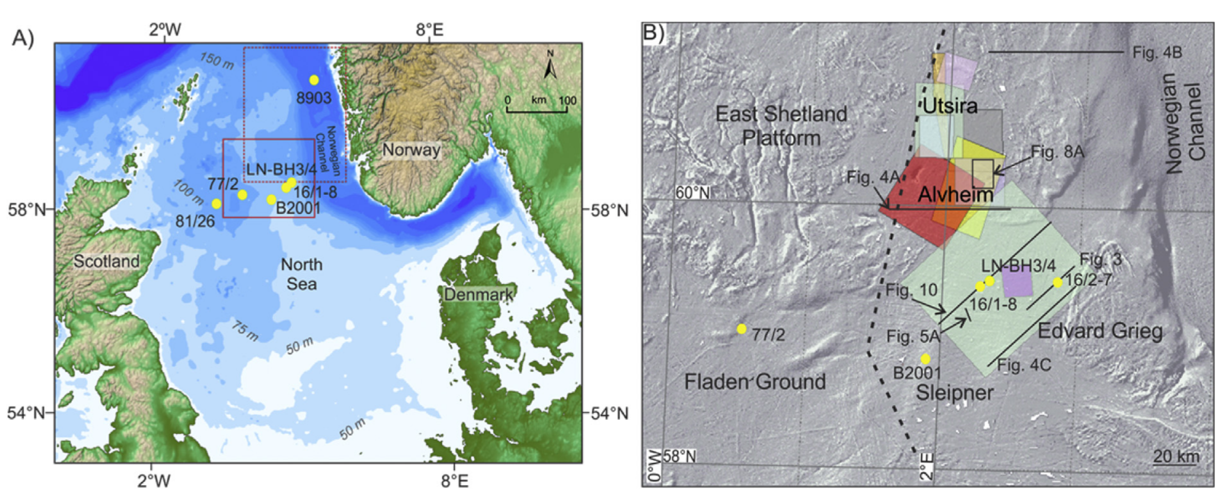

Fig. 1. A) Map of the North Sea with red box indicating location of study area detailed in 1B and dashed red box indicating area covered by the Petroleum Geo-Services Mega Survey. Also included are locations of shallow boreholes discussed in text. (B) Relief-shaded elevation map from the Olex database (Olex AS; www.olex.no). Coloured blocks indicate location of 3D seismic cubes used in study. The small dark purple box indicates an area where parametric sub-bottom profiler (TOPAS) data was collected. Dashed black line indicates boundary between British and Norwegian sectors of the North Sea. Yellow dots mark well and shallow borehole locations that were sampled for this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)